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THE TROTTER-PATERSON MEMORIAL LECTURE

The Brightness of the Stars

By SIR HAROLD SPENCER JONES, Sc.D., F.R.S. (*Astronomer Royal*)

The precise measurement of the apparent brightness of the stars forms an important branch of astronomy, called stellar photometry: important, because upon it depend the determinations of the distances of remote objects in the heavens. If, by one means or another, the intrinsic brightness of any celestial object can be assigned, a knowledge of its apparent brightness will enable its distance to be inferred by the use of the inverse square law. The determination of stellar distances by direct triangulation has a limited application; such determinations are based on the measurement of the small parallactic displacements in the position of the star resulting from the orbital revolution of the Earth round the Sun. The greater the distance, the smaller are these displacements; the method has reached its useful limit when the errors of measurement become equal to or greater than the angle to be measured. This limit is reached at a distance of about several hundred light-years. All determinations of the distances of more remote objects depend, either directly or indirectly, upon measurements of brightness; inasmuch, however, as such methods require a knowledge of the intrinsic brightness of these objects, they are based ultimately upon the direct measurements of the distances of the nearer stars, for it is only through such measurements that the basic knowledge of the intrinsic brightness of different classes of stars can be obtained.

The Greek astronomer, Hipparchus, in the second century B.C., divided the naked eye stars into six classes according to their brightness. The brightest stars were called stars of the first magnitude; the faintest stars that were comfortably visible to the naked eye on a clear moonless night were called stars of the sixth magnitude; the stars of intermediate brightness were designated as second, third, fourth or fifth magnitude. Gradations of brightness between adjacent classes were recognised by attaching the words "greater" or "less" to a magnitude, to denote that the star was somewhat brighter or fainter than that magnitude. These estimates of stellar magnitude have been preserved for us by Ptolemy who, in his great work known as the *Almagest*, gave the positions and magnitude of some 1,000 stars, based on the observations of Hipparchus.

Hipparchus, in effect, graded the stars according to their relative apparent brightness, and his six classes represent rough estimates of visual sensation. In designating these classes by numbers, increasing with decreasing brightness, he introduced a system of assignment of magnitudes which has been followed ever since.

In succeeding centuries, various astronomers, including Al Sufi, Ulugh Beg, Tycho Brahe, Hevelius and Flamsteed, repeated and improved upon the magnitude system of Hipparchus and extended it to more stars. The star catalogue of Flamsteed, published in his *Historia Coelestis*, gave the magnitude estimates for about 3,000 stars. During the eighteenth century, as the use of telescopes for meridian observations became general, a rapid increase took place in the number of stars catalogued for position, and it was customary for the observer to estimate the magnitude of each star as it transited across the field of view of his telescope. The magnitude system was extended to fainter stars and there was some increase in the precision of the estimates of magnitude. The magnitude classes were first sub-divided decimally, so as to represent more accurately the relative brightness of individual stars, by Argelander and Schönfeld in the preparation of the extensive survey of the sky, known as the Bonner Durchmusterung,

The third Trotter-Paterson Memorial Lecture delivered at the Royal Institution, London, on March 9, 1955.

extending from the North Celestial Pole to south declination 23 deg. and containing more than 500,000 stars. This Durchmusterung was later extended to the South Pole by Thome and Gould at Cordoba. With the decimal subdivision, the brightness of a star whose magnitude was assigned as 8.3 was between those of stars of magnitudes 8 and 9, and was judged to be three-tenths of the interval fainter than the star of magnitude 8.0.

The magnitudes of stars assigned by different observers by purely visual estimation, before the era of precise photometric measurement, were in tolerably fair agreement for the brighter stars. But the various estimates of the magnitudes of telescopic stars, which involved extrapolation beyond the naked eye limit of the Hipparchus-Ptolemy system, became increasingly discordant the fainter the stars. Thus, for instance, Wilhelm Struve estimated that the faintest stars visible in a telescope of 24 cms. aperture were of the 12th to 13th magnitude, whereas John Herschel estimated them to be of the 20th magnitude. Struve's scale has since been shown to be much nearer the truth that Herschel's.

In 1859 Fechner enunciated his psychophysical law according to which, as a stimulus increases in geometrical progression, its resulting sensation increases in arithmetical progression. This law requires that the ratio of the brightness of any two consecutive magnitude classes should be a constant. If I_m denotes the brightness corresponding to magnitude m,

$$I_m = \rho I_{m+1}$$

$$\text{or } \log \frac{I_m}{I_{m+1}} = \log \rho$$

where ρ is a constant, the same for all values of m.

Hence

$$\log \frac{I_{m_2}}{I_{m_1}} = (m_1 - m_2) \log \rho$$

That the brightness ratio of consecutive magnitude classes was approximately constant had been recognised before Fechner formulated his law. Steinheil had discovered it empirically in 1836 and had obtained a value of 2.83 for the quantity ρ. Somewhat later, investigations at Oxford by Johnson gave a value of 2.65 and others by Pogson gave a value of 2.40. The corresponding values of log ρ are 0.452, 0.423, 0.380.

Pogson in 1856 suggested that it would be convenient to adopt the value 0.4 for log ρ, corresponding to the value 2.512 for ρ, to define a precise photometric scale of magnitudes. With this value for ρ, which is very close to the mean of the values derived by Johnson and Pogson, a ratio in brightness of 100 to 1 corresponds exactly to a difference of five magnitudes. The adoption of a fixed value for ρ gives logical precision to the conception of magnitude, while Pogson's value is sufficiently in accordance with the earlier estimates to avoid serious discontinuity. The scale of magnitudes defined in this way is called the Pogson Normal Scale, and all modern determinations of magnitude are based upon it. Once the zero point of the scale has been chosen, the scale can be extended in both directions. The magnitude of a star can be given with as many decimals as the precision of the photometric determination of its brightness warrants. The brightest stars, the bright planets, the Moon, and the Sun have magnitudes which are expressed as negative quantities. A star 2.512 times brighter than a star of magnitude 1.0, for instance, has a magnitude of 0.0; a star 2.512 times brighter than a star of magnitude 0.0 has a magnitude of -1.0, and so on.

It is of interest to see how some of the visual estimates of magnitude compare with the Pogson scale. In the following table are given the mean magnitudes on the

Pogson scale of groups of stars corresponding to integral magnitudes in the scales of Ptolemy (*c.*140 A.D.), Tycho Brahe (*c.*1590), Argelander (*c.*1850) and Gould (*c.*1875):—

m	Ptolemy	Tycho Brahe	Argelander	Gould
1.0	1.0	0.9	0.6	0.8
	1.4	1.5	1.7	1.5
2.0	2.4	2.4	2.3	2.3
	1.2	1.1	1.1	1.0
3.0	3.6	3.5	3.4	3.3
	0.9	0.8	0.9	0.9
4.0	4.5	4.3	4.3	4.2
	0.5	0.5	0.8	0.8
5.0	5.0	4.8	5.1	5.0
	0.3	0.4	0.9	0.9
6.0	5.3	5.2	6.0	5.9

It will be seen that all the estimates depart in the same sense from a true photometric scale at the bright end of the range, the interval of one magnitude as estimated by each of these observers being too great. For the fainter stars the magnitude interval adopted by Ptolemy, and following him by Tycho Brahe, was much too small, whereas both Argelander and Gould assigned magnitudes that were more nearly in accord with the normal scale. Thus in the early magnitude assignments, a true interval of one magnitude was over-estimated at the bright end of the scale and under-estimated at the faint end.

The system of magnitudes, introduced more than 2,000 years ago to provide a rough grading of the brighter stars according to brightness and which, as we have seen, was an approximate measure of physiological sensation, became, with the introduction of the Pogson Normal Scale, a physical concept, a given difference of magnitude corresponding to a definite assignable ratio of brightness or, in other words, of energy flux per unit area received by the observer.

Thus a measurement of the intensity of the light received from a star is needed for finding its magnitude. Many different types of photometer have been designed and employed for this purpose; the basic principle of all of them is the determination of the relative brightness of two stars either by diminishing the brightness of one or both of their images until they appear equally bright, or by comparing the brightness of each in turn with the brightness of an artificial star, which is assumed not to change in brightness between the two comparisons. For the purpose of securing the equality in brightness, either some form of polarising device or a neutral tinted wedge of graduated absorption has normally been used. The extensive visual photometric observations at the Potsdam Observatory, from which were compiled the *Potsdamer Photometrische Durchmusterung*, giving the visual magnitudes of 14,199 stars to the 7.5 magnitude in the northern hemisphere, were made with a Zöllner photometer, in which the light from an artificial star is polarised and reduced in brightness by turning a Nicol prism until it is judged to be equal to the unpolarised light of the star under observation. The still more extensive observations of the Harvard Observatory provided, in the *Revised Harvard Photometry*, the magnitudes of 45,792 of the brighter stars all over the sky. Most of the Harvard observations were made with a meridian photometer, with which the light from a star when on or near the meridian is compared with the light of the Pole star. Two mirrors feed the light from the two stars into a telescope, placed horizontally in the east-west direction, and provided with two equal objectives. The two beams pass through a polarising double-image prism; the ordinary beam from the one star and the extraordinary beam from the other pass through the eyepiece and then through a Nicol prism, which is rotated until the star images appear equally bright.

Many precautions are needed to obtain accuracy in such measures. The paths

of the two beams of light through the photometer should be as nearly identical as possible so that their absorption in the photometer should be equal. The two images should be brought as close together as possible, to minimise effects of non-uniform sensitivity of the retina. In general if two images A and B appear equally bright when B is to the right of A, they will not appear equally bright when B is to the left of A, or when it is above or below A. The use of a reversing eyepiece for interchanging positions is thus desirable.

The use of an artificial star, as in the Zöllner photometer, introduces difficulties, for an artificial star image can never be made to look exactly like that of a real star, because of the effects of atmospheric scintillation. The two stars whose brightness is to be compared should be as nearly as possible at the same zenith distance, to equalise approximately the effects of atmospheric absorption. With the meridian photometer this requirement cannot be met, and the difference in the atmospheric absorption for the two stars can be only approximately allowed for.

The most serious of all sources of error in visual comparisons arises from a difference of colour of the stars to be observed. The estimation by the eye of the equality of brightness of two sources of different colour is peculiarly difficult, and is liable to large personal errors caused by differences in the colour sensitivities of the eyes of various observers. Moreover the Purkinje effect cannot be avoided; if two sources which differ in colour are judged to be equally bright, then, if each source is increased in brightness by the same factor, they will no longer appear equally bright; the redder of the two will appear the brighter. Conversely, if each source is reduced in brightness by the same factor, the bluer of the two will appear the brighter.

No two observers, in fact, have eyes which are precisely equal in the distribution of retinal sensitivity to both colour and intensity. Magnitudes determined by different observers will therefore not be in agreement; there will be differences which will be correlated with the colours of the stars amongst other factors. It might be suggested that a visual scale of magnitudes could be formed to represent the average human eye. This is not, however, practical and for precise photometry the eye has had to be abandoned in favour of other methods which are not subject to the same difficulties.

But before considering other methods, it is desirable to consider in greater detail precisely what is involved in the measurement of the magnitude of a star. A star radiates approximately like a black body, the radiation being spread over a wide range in wave-length in accordance with Planck's Law. The distribution of the radiation amongst the various wave-lengths therefore depends upon the temperature of the star or, which is equivalent, upon its colour.

What we should like to be able to measure is the total luminous flux of energy from the star per unit area of the cross section of the beam on the outside of the Earth's atmosphere. But we have to make our measurements from the bottom or from near the bottom of the atmosphere surrounding the Earth. The atmosphere absorbs some of the energy; this absorption depends upon the length of the path of the light through the atmosphere, and therefore upon the zenith distance of the star, and furthermore it is selective in its amount. The ozone layer in the upper atmosphere absorbs all the light on the short wave-length side of 0.29μ, while water-vapour, carbon dioxide, oxygen and other atmospheric constituents each absorb light in various parts of the spectrum; the absorption by water-vapour furthermore varies appreciably with the humidity of the atmosphere.

Atmospheric absorption is the most troublesome of all the complicating factors involved in the measurement of stellar magnitudes. It depends not merely upon the zenith distance of the star and upon the wave-length of the light but also upon the locality. Obviously it is greater when observations are made at ground level than when they are made on a mountain top; at ground level it is greater in an industrialised area than in open country. It is, moreover, variable with time; variations in visibility

from day to day are familiar to everybody; but variations in absorption may occur from hour to hour and even from minute to minute. Even so, the atmospheric transparency is not normally the same in all azimuths. Inequalities of absorption in different azimuths can be averaged out to some extent by repeated observations on different nights; if, however, the observatory is in the vicinity of a city, as many observatories are, atmospheric transparency may be systematically lower in certain azimuths than in others. In precise magnitude determinations, it is the atmospheric absorption that sets a limit to the accuracy attainable. In this field of work it is wise to restrict observations to the best nights, which occur infrequently.

The starlight, having penetrated the atmosphere, is collected by a telescope. The optical train of the telescope transmits only a fraction of the incident light, and the transmission is different for different wave-lengths. The dependence of the transmission on wave-length will be greater for a refracting telescope, in which the light passes through the objective, than for a reflecting telescope in which the light is reflected from a film of silver or aluminium. The transmission may change with time as the consequence, for instance, of the gradual tarnishing or diminution of reflectivity of this film.

Finally some form of receiver has to be employed, which may be the eye, or a photographic plate, or a photocell. The response of this receiver will be different for different wave-lengths. When a physical receiver is used, its response under specified conditions is determinable. The human eye presents more complications than a physical receiver; its response can depend, for instance, on the total brightness, through the Purkinje effect.

The various factors that I have mentioned can be combined into a mathematical formula. The magnitude m is related to B, the total luminous flux effective on the receiver by the relation

$$m = -2.5 \log B + k$$

in which the factor 2.5 is Pogson's coefficient and k is a constant which defines the zero point of the magnitude scale.

If r is the radius of the star, ρ its distance, and $E(\lambda)d\lambda$ is the energy flux emitted by the star for the wave-length interval λ to $\lambda + d\lambda$ per unit solid angle per unit area of its surface, then

$$B = \int_0^\infty \frac{\pi r^2}{\rho^2} E(\lambda)\phi(\lambda)d\lambda$$

where $\phi(\lambda)$ is the fraction of the energy transmitted through the earth's atmosphere, then through the optical system used, and finally responded to and absorbed by the receiver employed.

$$\text{Also} \quad \phi(\lambda) = P\, A(\lambda)\, T(\lambda)\, R(\lambda)$$

where P denotes the area of the telescope aperture in cm^2;

$A(\lambda)$ is the fraction of the energy transmitted by the atmosphere of the earth at wave-length λ;

$T(\lambda)$ is the fraction of the energy incident on the optical train which is transmitted by it;

$R(\lambda)$ is the response of the light receiver at wave-length λ.

As already mentioned, $\phi(\lambda)$ depends not only on λ but also on the zenith distance of the star and varies with locality and with time.

The definition of the brightness B and hence of the magnitude m can consequently only have a precise interpretation if all the factors are specified. A system of stellar magnitudes can be defined by specifying a definite receiver attached to a definite telescope working in a definite place with definite atmospheric transmission.

But in practice matters are not quite as bad as they may appear at first sight.

For it is not the brightness B of an individual star that is measured, but always the ratio of the brightness of two stars. This fact is concealed in the zero-point constant of the relation between magnitude and brightness. It is always differences of magnitudes of pairs of stars that are measured; the zero-point of the system of magnitudes is arbitrary and has to be fixed by some agreed convention. When comparing the brightness of two stars, the transmission of the optical train will be approximately the same for each star; the atmospheric absorptions will be approximately equal provided the stars are observed at the same altitude. Slight differences are probable if the stars differ in colour. Slow changes in atmospheric transmission can be mostly eliminated by observing the first star both before and after the second, while the effects of random differences in atmospheric absorption in different azimuths can be reduced by repeating observations on several nights.

Systems of stellar magnitudes taken with different instruments and at different times but by essentially the same method (e.g., by using photographic plates with the same type of emulsion) may therefore be expected to show slight differences which will depend upon the colours of the individual stars. Small errors in the scale factor, the Pogson coefficient, of each series are also probable. The differences between two magnitude systems of the same general type can consequently be represented by an expression of the form $\alpha m + \beta C + \gamma$ where C is a measure of the colour of the star.

The practical procedure for co-ordinating the diverse magnitude systems derived with different instruments is first to adopt a certain system of magnitudes as a standard reference system, and then to reduce each observed system as nearly as possible to the standard system by comparing the observed magnitudes of stars common to both systems with the magnitudes of the standard system. The differences of magnitudes are represented by a formula of the above type, from which the constants α, β, γ, are determined. These constants may then be used to reduce the magnitudes of all other stars to the standard system. It may be noted that it is an essential requirement of this procedure that the colours of the stars common to the two series of magnitudes should be known.

I mentioned earlier the two important series of visual determinations of magnitude at the Potsdam and Harvard Observatories. The zero-point of the Potsdam system was chosen so that the average magnitude of the 144 standard stars (about 6.0) on which the system was based agreed with the average magnitude of the same stars as given in the Bonn Durchmusterung by Argelander. The zero-point of the Harvard system was chosen so that the average magnitude of 100 northern standard stars (about 4.0) agreed with the average magnitude of the same stars as given by Argelander. As Argelander's zero-point was based on the magnitude system of Hipparchus and Ptolemy, the zero-point of both the Potsdam and Harvard systems trace back essentially to the early Greek magnitude estimates. There is a small difference in scale between these two systems and at magnitude 5.0 the Potsdam magnitudes are 0.2m brighter than the Harvard; this difference is not surprising, as the two systems had their zero-points standardised against different points in Argelander's scale.

The internationally adopted standard of reference is provided by the magnitudes of a selected sequence of stars in the vicinity of the north celestial pole, known as the North Polar Sequence. The initial selection of stars in this sequence was made at the Harvard Observatory and the magnitudes were derived from extended series of visual observations with the meridian photometer.

The application of photography to astronomy was soon followed by its employment for photometric observations. The early emulsions were all of the normal blue-sensitive type and it was soon realised that the system of magnitudes determined

photographically differed from the visual system. As compared with the eye, the photographic plate is relatively more sensitive to blue light and less sensitive to red. The difference between the photographic and visual magnitudes of a star therefore provides a measure of the colour of the star, called the *colour index*, which increases progressively with change of colour from the blue to the red stars.

When a panchromatic emulsion is used in conjunction with a suitable colour filter, a colour rendering is obtained which approximates to that of the human eye. A system of magnitudes can then be derived which simulates the visual system closely. This photovisual system, as it is called, has superseded the purely visual system. It has the advantage that it is free from the troubles associated with the Purkinje effect, and the use of photography has enabled the system to be extended to stars of magnitudes fainter than can be observed visually.

The photographic magnitudes of the stars of the North Polar Sequence were determined at the Harvard Observatory with the aid of 13 instruments with apertures from ½ in. to 60 in. Many different methods for establishing the scale of magnitudes were used at Harvard, such as placing wire screens or circular diaphragms in front of the objective, or covering each half of the objective in turn, to give differences of magnitudes of amounts that could be accurately calculated. The photographic and photovisual magnitudes have since been determined at various other observatories and the sequence has been extended to magnitude 21.0 on the photographic scale and to 17.4 on the photovisual scale. The magnitude scale has been established by various methods in addition to those used at Harvard. A method much employed is to place a coarse wire screen in front of the objective; each star image is then accompanied on either side by a diffracted image whose magnitude differs from that of the central image by a constant value, which can be calculated accurately from the dimensions of the bars and spaces of the grating. Different magnitude reductions can be obtained by suitable choice of the thickness of the bars and of their spacing. An advantage of this method is that it is not affected by changes in atmospheric transparency during the exposures.

Another method is to employ a neutral absorbing half filter, i.e., a filter of which one half is clear glass, while the other half has a neutral tint giving a non-selective absorption whose amount depends upon the density of the filter. Two equal exposures are given on the field of stars in succession, the filter being reversed between them, so that two images are formed of each star, the magnitude difference between the two images of every star being the same.

A different type of method uses extra-focal images, whose densities are measured by a suitable type of photometer. The densities of the star images are standardised by calibrating the plate in the laboratory with a tube sensitometer. This type of sensitometer is provided with a series of tubes, having identical apertures at the end facing the photographic plate; at the other end of each tube is a small circular aperture. These apertures are graded in size, their diameters being measured with great accuracy under a microscope. The apertures are illuminated by a uniformly bright diffuse source of light. The plate is exposed in the sensitometer for a time equal to the duration of the star exposure, a series of sensitometer spots, graded in density, being obtained; these spots, whose relative intensities are accurately known, are used for standardising the out-of-focus star images.

The method known as the Fabry method has the advantage of being capable of very high accuracy; as, however, only one star at a time can be observed, its use is generally restricted to building up a standard sequence. A small auxiliary lens, of focal length about 1 in., is inserted in the converging beam near the focus of the objective; it forms an image of the objective on the photographic plate by the light of the star under observation. The image is of uniform surface brightness and is in consequence particularly suitable for accurate photometry. Good results are obtained

even with a telescope of indifferent optical performance; thus, for instance, a visual telescope can be used for photographic observation by this method. Accurate guiding of the telescope during the exposure is not required and, as scintillation effects are averaged out during the exposure, a steady atmosphere—what the astronomer calls good "seeing"—is not critical. The method is useful for determining the integrated magnitude of irregular objects, such as small nebulae or star clusters, whose observation is difficult by other methods because their images are not uniform. The plates can be standardised either by a tube sensitometer, or by an intermittent sensitometer, which is provided with a sector wheel with graduated openings. The sector is rotated at a high speed and exposures of equal duration are made through each of the openings in succession.

The zero of the photographic scale of magnitudes was decided by international agreement to be such that the mean photographic magnitude of stars of spectral type A_0 (white stars) between magnitudes 5.5 and 6.5 should equal the mean Harvard visual magnitudes of those stars. The colour index of an A_0 star is thereby given the value zero.

The adopted photographic and photovisual magnitudes of the 96 stars of the North Polar Sequence form the fundamental system of reference for all magnitude determinations. The magnitudes are based on investigations at many different observatories, most of which are concerned with a portion of the sequence only. The range of about 20 magnitudes corresponds to a ratio of 100 million to one in brightness. Such a great range can be covered only in a number of separate steps. To piece these steps together and to co-ordinate the investigations of different observatories, while endeavouring to ensure that the whole sequence is accurately on the normal scale, has entailed an immense amount of work, with many successive approximations. The whole task was directed by Dr. F. H. Seares of the Mount Wilson Observatory, who was the President of the Commission on Stellar Photometry of the International Astronomical Union.

In the magnitudes of the two scales as finally fixed, the colour index for A_0 stars proves to be not quite zero, as originally planned, but -0.04 magnitude instead. Furthermore, it has been found that the polar area is slightly obscured by a thin veil of interstellar dust cloud, the effect of which is to make the stars redder than stars in unobscured regions by about 0.1 magnitude. The effect of this, combined with the colour index of -0.04 for the A_0 stars, is that the colour indices of A_0 stars in unobscured regions, whose magnitudes have been derived by comparison with the polar standards, average about -0.14 magnitude. The original definition of the zero of the magnitude scale has consequently been abandoned and the Polar Sequence magnitudes are now accepted as defining the zero points.

The magnitudes of stars in other regions of the sky which can be observed at the altitude of the Pole can be determined by photographing the polar area on the same plates and using the Polar Sequence magnitudes as standards of reference. It is usual to employ some type of physical photometer for the comparison, using purely physical methods to obtain accuracy. For instance, light from a constant voltage lamp can be condensed by a microscope objective on to the photographic plate. The beam of light passing through the plate is projected on to a thermopile or a photocell and the current generated is measured by the deflection of a galvanometer. A star image is then placed in the centre of the bright spot and the reduced deflection is measured. The difference of the deflections is a measure of the blackening or the star image. These differences, when plotted against magnitude for the Polar Sequence stars, provide a calibration curve for deriving the magnitudes of the field stars.

Regions of low declination cannot be observed at the same altitude as the Pole. It is necessary to standardise such regions against one or more regions of higher declination, which have been standardised by direct polar comparison.

The transfer of the photometric system of the North Polar Sequence to other parts of the sky in this way is not without difficulty, for the standards are few in any particular magnitude range and are rather far apart. They can be conveniently used only with cameras which cover a wide field, and such cameras usually entail the complication of requiring corrections to the measured magnitudes depending on distance from the centre of the field, on colour, and also on brightness. To remedy the difficulty Seares and his collaborators at Mount Wilson have determined the photographic and photovisual magnitudes of 2,271 stars in the area extending 10 deg. in all directions around the Pole, on the system of the North Polar Sequence.

During recent years the photoelectric cell has been increasingly used for the precise photometry of stars. The photosensitive cathode is superior in quantum efficiency to the photographic plate. Whereas about 100 quanta of energy are required to produce a single developable grain in a photographic emulsion at a wave-length of 0.4μ, about one in eight incident quanta produce a photoelectron with a typical antimony-caesium surface and, in exceptional cases, the efficiency is as high as one in four. Although in the red and the near infra-red region the efficiency of the best photoelectric cathode. the caesium oxide on silver, is much lower, it still remains higher than that of the red sensitive photographic plate at such wave-lengths. The photoelectric cathode possesses the further very great advantage that its response to the incident energy is very closely proportional to the intensity over a wide range, whereas the response of the photographic plate is not linear and for any particular type of emulsion approximates to linearity only within a comparatively narrow range of intensity. The photoelectric cell, on the other hand, is at a disadvantage compared with the photographic plate in that it is possible to observe only one star at a time, so that the photographic plate is more economical in its use of telescope time. The photoelectric cell can be used with various colour filters and it is possible, by appropriate choice of filters, to obtain responses that closely reproduce the photographic and photovisual scales of magnitude.

The photoelectric cell, because of its linear response, is ideal for the setting up of precise magnitude scales in different regions of the sky. It has also great advantages in variable star photometry, in which the brightness of a variable star is compared with the brightness of two or three nearby stars of constant brightness. The high accuracy which is attainable with the photoelectric cell under favourable observing conditions is particularly valuable in this field of investigation. With the Crossley 36-in. reflector of the Lick Observatory, the probable error of a single magnitude determination, using a photoelectric cell with electron multiplier, is $\pm$ $0^m.003$ at magnitude 13 and $\pm$ 0^m03 at magnitude 16. With a 100-in. telescope under the same conditions these probable errors should be reached for stars of magnitude 15.2 and 18.2 respectively. The probable error of a magnitude determination necessarily increases as the intensity of the source diminishes because it depends upon the signal to background noise ratio. The noise is caused in part by variable seeing and in part by the statistical fluctuation in the rate of release of electrons, even when the cell is irradiated with light of constant intensity, by the dark current of the cell, and by the residual grid current of the amplifying tube. The noise arising from the apparatus itself remains about the same when the signal strength is diminished; hence the signal to noise ratio decreases and the errors of observation increase with reduction in signal intensity.

The measurement of photovisual and photographic magnitudes of stars has followed from the natural historical development of stellar photometry, first the eye and then the photographic plate being employed as the receiver of the stellar radiation. The two together provide a measure of the colour of the star, though a colour measurement could be made independently of either. It may be suggested that it would be more useful to measure the total radiation from the stars by the employment of

thermocouples or bolometers, which are equally sensitive to radiations of all wavelengths. But apart from the fact that such receivers are not so sensitive as the photographic plate or the photo-emissive cathode to radiation of very low intensity, little gain would result from their use because our terrestrial atmosphere would remain as an impenetrable barrier to prevent the measurement of the total output of energy from a star.

I mentioned at the outset that the measurement of the apparent brightness of the stars was important because the determination of the distances of remote objects depended upon such measurements. Let us return to the formula already given

$$m = -2.5 \log \int_0^\infty \frac{\pi r^2}{\rho^2} E(\lambda)\, \phi(\lambda)\, d\lambda + k$$

where ρ denotes, as you will remember, the distance of the star. This formula can be rewritten in the form

$$m = -2.5 \log \int_0^\infty \frac{\pi r^2}{\rho_0^2} E(\lambda)\, \phi(\lambda)\, d\lambda + 2.5 \log \frac{\rho^2}{\rho_0^2} + k$$

$$= M_0 + 5.0 \log \frac{\rho}{\rho_0}$$

where M_0 denotes the magnitude that the star would have if brought to a standard distance ρ_0. If the stars were all brought to the same distance, their apparent magnitudes could be used as measures of their intrinsic luminosities. The conventional standard distance used in astronomy is 10 parsecs (32.6 light years) and the magnitude of an object at this distance is called its absolute magnitude. If the intrinsic luminosity of a star or other celestial object is known from its physical characteristics or in other ways, M_0 can be calculated. The above formula will then enable the distance of the object to be inferred when its apparent magnitude has been determined.

With long exposures under good conditions the 100-inch reflector on Mount Wilson records distant galaxies, which can be distinguished from stars, as faint as magnitude 21.5. The 200-in. reflector on Mount Palomar will distinguish galaxies to magnitude 23.0. The ratio of the apparent brightness of the Sun to that of such a distant galaxy is about 80 million million million. The establishment of a scale of magnitudes that is accurate over so vast a range of intensity is a task of immense complication. The astronomer has to deal for the most part with intensities that are extremely weak compared with those with which the physicist is normally concerned. The total light received from all the stars is only about 1/100 of that received from the Moon, and is about equal in photographic intensity to that of an ordinary 16-candle power lamp at a distance of 47 yards.

An important question in cosmology is whether, at the greatest depths to which we can penetrate space—about 2,000 million light years with the 200-in. telescope—there is any evidence of a thinning out in the spatial density of the galaxies. One essential requirement for an answer to this question is the establishment of an accurate scale of magnitudes to beyond the 23rd magnitude. Hubble, in his book *The Realm of the Nebulae*, which dealt with the results of surveys made with the 100-in. telescope, ended with these words: "Thus the explorations of space end on a note of uncertainty. And necessarily so. We are, by definition, in the very centre of the observable region. We know our immediate neighbourhood rather intimately. With increasing distance, our knowledge fades, and fades rapidly. Eventually, we reach the dim boundary—the utmost limits of our telescopes. There, we measure shadows, and we search amongst ghostly errors of measurement for landmarks that are scarcely more substantial. The search will continue. Not until the empirical resources are exhausted, need we pass on to the dreamy realms of speculation."

Electroluminescence

By J. N. BOWTELL, B.Sc. A.Inst.P. *(Member)*, and H. C. BATE, B.Sc.

Summary

This paper deals with the main features of electroluminescence and emphasises aspects of particular interest to illuminating engineers. Following a brief account of earlier work, the design, construction and performance of practical electroluminescent light sources are described. Essential theoretical aspects are also mentioned.

Certain specialised applications of electroluminescence for photographic and other purposes are discussed. Reference is also made to possible future uses for this light source.

Introduction

Electroluminescence may be defined as the emission of light from a phosphor excited directly by an electric field. Under this definition is included the work of Gudden and Pohl[1], who showed that the afterglow decay of certain phosphors could be accelerated by the application of an electric field. Also, Lossev and others[2, 3, 4, 5] demonstrated that light could be obtained from a carborundum crystal through which a current is made to flow.

This paper is, however, mainly concerned with developments arising from a discovery by Destriau[6] that light can be obtained continuously from certain specially prepared zinc sulphide phosphors directly excited by a varying electric field. He constructed cells based on this principle and operated them from normal A.C. supply mains. He further suggested that the new phenomenon could form the basis of a practical light source.

Construction of Electroluminescent Devices

Fig. 1 shows diagrammatically the type of cell used by Destriau in his investigations into electroluminescence. This comprised a metal platform which served as one plate or electrode of a capacitor, and supported a thin layer of the phosphor dispersed in a resin or insulating oil. This in turn was covered with a thin sheet of mica on which was spread an electrically conducting salt solution, forming the second plate or electrode and enabling the phosphor to be subjected to relatively intense electric fields. Being at the same time transparent, the salt solution permitted the light from the phosphor to emerge. This simple device greatly facilitated the study of a variety of phosphors and insulating media.

Fig. 2 shows front and back views of a group of modern electroluminescent panels, and Fig. 3 depicts their construction. Although similar in principle, there are marked differences from Destriau's cell. The main supporting member is a piece of sheet glass one surface of which is treated to render it conductive without undue loss of

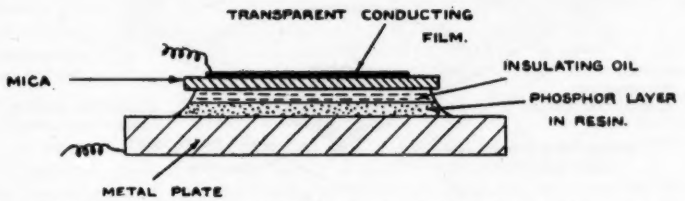

Fig. 1. Section of cell used by Destriau for study of electroluminescence.

Communication from the Staff of the Research Laboratories of The General Electric Co., Ltd., Wembley, England. The manuscript of this paper was first received on March 4, 1955, and in revised form on March 17, 1955. The paper was presented at a meeting of the Society held in London on April 19, 1955.

transparency. This forms one electrode of the capacitor, the other being an opaque (and usually reflecting) layer of conducting material. Between the two is sandwiched the dielectric layer consisting of the phosphor dispersed in a suitable solid insulating material. The panel is then finished with a robust insulating backing. Contact is made to the two conducting surfaces by means of small metallic pieces. One is cemented directly to the transparent conducting surface. The other, which is connected to the opaque electrode, is also mounted on this surface but with an intervening insulating layer. The contacts are arranged to be flush with the protective backing in the finished panel, and are preferably mounted at the corners since in this position less of the front face of the panel is obscured[7, 8].

A number of variations of this construction have been proposed[9, 10, 11]. The opaque electrode could be replaced by another glass sheet with transparent conducting rayer, permitting emission of light from both sides of the panel. The glass plate need not be planar; Fig. 4 shows an example of an electroluminescent lamp in which the various layers have been coated on the inside of a conventional filament lamp bulb finished with a standard bayonet cap in the normal way. A tubular bulb, as used for fluorescent lamps, provides another possible shape of envelope. This so-called "enclosed" construction has the advantage that the bulb can be filled with a dry inert gas which, as discussed later, improves lumen maintenance.

In the development of practical electroluminescent devices, much attention has

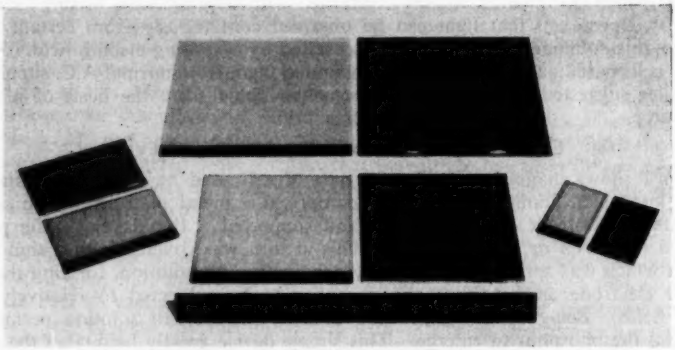

Fig. 2. Electroluminescent panels of various sizes showing front and rear surfaces.

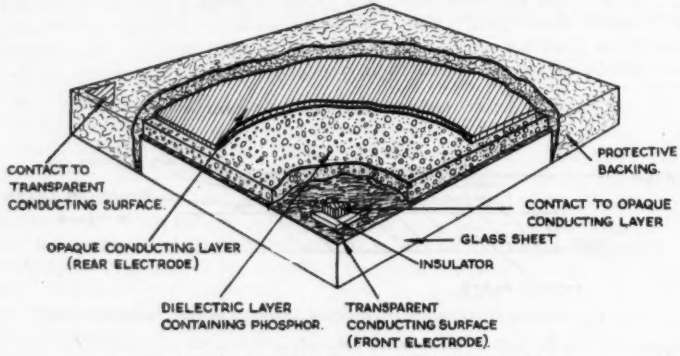

Fig. 3. Construction of electroluminescent panel.

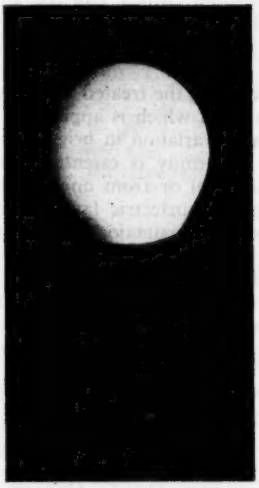

Fig. 4. Example of electroluminescent lamp using standard filament lamp bulb and cap.

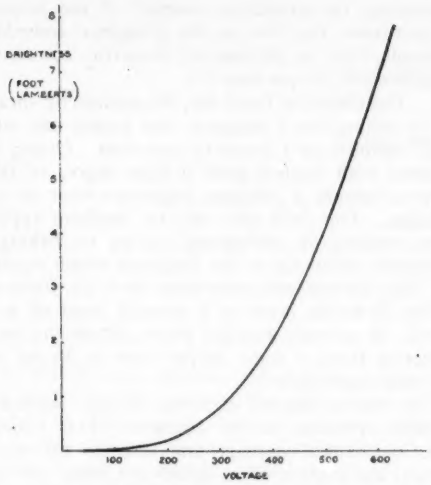

Fig. 5. Relationship between voltage and brightness for a green electroluminescent panel.

perforce been given to the materials used and their method of application. At each stage of manufacture there is usually a number of possible materials for each of which there are several methods of application. The selection, therefore, of an acceptable manufacturing technique to give panels of good quality is a matter of considerable difficulty.

The treatment of the glass plate to render one surface conducting is now a relatively straightforward process[12]. The sheet of glass is subjected, at a temperature near its softening point, to the action of a tin compound, causing atoms of tin to diffuse into the surface to form a thin semiconducting layer about 1 micron thick. Such a layer has a surface resistivity of about 500 ohms per unit square and an additional light absorption over the untreated sheet of about 15 per cent. Much lower resistances can be obtained with further reduction in transmission, but the value quoted is satisfactory for electroluminescent devices operating from supply frequencies up to 1,000 c.p.s. Conducting films of cadmium oxide and gold have also been proposed[13], but not generally used for electroluminescent panels.

Apart from the phosphor, the resin in which it is dispersed to form the dielectric layer has by far the greatest influence on the performance of a panel. Its main requirements are high dielectric strength, high dielectric constant, and good adhesion to the glass plate. It must be chemically inert towards the phosphor, and have good film forming properties for spray or dip application. Lacquers based on the alkyd-type resins are found to be fairly satisfactory[14]. Nitrocellulose has also been used and recently it has been reported that vitreous dielectrics give good results[15]. There are, however, no materials readily available which are ideally suitable for this purpose, and it can be said that future progress in the application of electroluminescence is closely dependent upon the development of suitable dielectric media.

The requirement of high dielectric strength arises from the fact that the brightness of a panel increases rapidly with voltage as shown in Fig. 5. Increase in dielectric strength enables a panel to be operated without breakdown at a higher voltage, with consequent increase in brightness. Also higher brightness may be obtained by

increasing the dielectric constant of the suspending medium, which has the effect of increasing the field on the phosphor embedded in it. It has been shown, for example, that an increase in dielectric constant from four to eight increases the brightness by 90 per cent.[16].

The dielectric layer may be applied by spraying or dipping the treated glass sheet, or by rolling out a phosphor and plastic mix into a thin sheet which is applied to the glass member as a separate operation. Owing to the rapid variation in brightness of a panel with applied field, a high degree of thickness uniformity is essential in the layer to ensure a constant brightness over an individual panel or from one panel to another. This calls not only for uniform application of the dielectric layer but for close control of subsequent drying or baking processes to maintain constant the inevitable shrinkage in the thickness which occurs.

The second electrode may take the form of an aluminium film evaporated on to the dielectric layer or a sprayed layer of a silver, copper or graphite conducting paint. A sprayed graphite paint affords the most economic process, but being non-reflecting there is some 10 per cent. to 30 per cent. loss in brightness compared with an aluminium film.

A final protective covering is then applied over the rear of the panel, leaving suitable apertures at the contacts. This backing must protect the layers beneath from mechanical damage and insulate the metallic layer electrically. It must also prevent the ingress of moisture and other contaminants to the layers beneath.

No entirely satisfactory backing material has so far been found. One which meets the requirements fairly well, and gives an attractive finish to the panel, takes the form of a layer of micanised shellac, flame-sprayed by the Schori technique[17, 18, 19]. Another consists of a paraffin-wax coating covered by a sheet of glass or plastic. This affords good protection but gives a somewhat thick and bulky construction.

Electroluminescent Phosphors

Zinc sulphides, suitably prepared, are by far the most important class of phosphor exhibiting electroluminescence[6, 20]. Zinc sulpho-selenides have also been reported as showing a relatively strong effect. Zinc cadmium sulphides and willemite may be classed as weakly electroluminescent[6], and as far as is known, have not been used in practical electroluminescent devices.

Normal zinc sulphides prepared with low activator concentration for excitation by ultra-violet radiation show little or no field excitation. The maximum electro-luminescent effect is obtained, in general, only when a relatively large amount of copper activator is present in the finished phosphor.

By suitable choice of activator and method of preparation, a range of colours from orange, through green, to blue have been developed[21, 22]. Phosphors giving a subjective white may be obtained by mixing orange and blue materials. An efficient red electroluminescent phosphor has not so far been reported. The availability of such a material would greatly facilitate the development of a white with good colour rendering properties.

Mechanism of Electroluminescence

The fundamental mechanism of electroluminescence has been intensively studied in recent years, producing a rapid growth in the literature on this subject[23, 24]. It is, however, far from being fully understood. A full discussion of this problem is not possible within the scope of the present paper, and what follows is intended to cover in simple terms only the broad principles involved.

The more familiar mechanism of fluorescence excited by ultra-violet radiation may be understood by reference to Fig. 6. Here the possible energies which an electron can possess within the lattice of a crystalline solid are represented by two bands, the lower or filled band in which there are normally no vacancies for electrons,

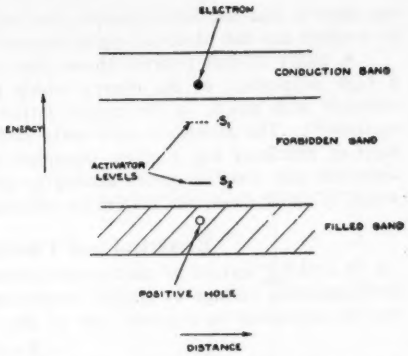

Fig. 6. Energy level diagram of impurity activated phosphor.

and the upper or conduction band in which electrons can move freely. The two bands are separated from each other by a forbidden region(25). Electrons cannot normally have energies corresponding to this region, except where activator atoms within the lattice give rise to energy states as shown at S_1 and S_2. Theory postulates that an incident U.V. photon raises an electron from the filled to the conduction band, leaving a region of negative charge deficiency (or positive hole as it is termed) in the filled band which is neutralised by an electron from an activator state S_2. An electron in the conduction band can then return to S_2 via S_1, with the emission of a photon of longer wave-length. Excitation of phoshors by cathode rays may also follow a similar mechanism whereby electrons in the filled band are raised to the conduction band by collision with bombarding electrons. Direct excitation of the activation centre may also take place in a similar manner by raising an electron from S_2 to S_1.

In addition to the normal field excitation, an electroluminescent phosphor usually shows fairly strong excitation by ultra-violet radiation and cathode rays. By all three methods of excitation, the spectral distribution of the emitted light is substantially the same. This suggests that the activator centres in an electroluminescent phosphor are responsible for the light emission in the normal way. The mechanism of electroluminescence must therefore provide a means whereby the applied electric field can excite the activator centre or move an electron from the field to the conduction band.

It is generally assumed that the direct action of even relatively strong fields (e.g., 10^6 volts per cm.) is unable to effect these transitions except in very small numbers insufficient to account for observed electroluminescent brightness values.

A striking feature however of electroluminescence is the unexpectedly low field strengths necessary to excite the phosphor. Panels can be made to emit light with as little as 5 volts R.M.S. applied to them, corresponding to an average applied potential gradient of 1,000 volts per cm., and under normal conditions they operate at the relatively low figure of 20,000 to 50,000 volts per cm.

A possible mechanism for the transfer of energy from the applied field to the activator centres is excitation by collision. This process is somewhat akin to cathode ray excitation. Electrons in the conduction band are presumed to be accelerated in the applied field and gain sufficient energy to excite the activation centres by collision.

However, making all possible allowances it can be shown that the applied field, if uniform, is still of an order too low to account for the electroluminescent brightness values obtained. It is well known that, in contrast to U.V. excited luminescence where the light is emitted more or less uniformly by the phosphor crystal, the emission of light from an electroluminescent phosphor occurs as minute bright spots where crystals are in contact, or at sharp points on their surfaces(26). Recent work

has shown that the field strength can reach sufficiently high values in these regions to account for the observed light output[23, 27].

A study of this process shows that during acceleration in the conduction band a high proportion of the energy which the electrons gain from the field is lost by collision with atoms in the crystal lattice before an activator centre is reached and excited[28]. The process is inherently inefficient and calculation shows that the upper limit of efficiency for a green phosphor is unlikely to exceed 12 lm/w. Additional dielectric and resistive losses arising in practical panels reduce this value to 6 lm/w, which is about twice the maximum efficiency value found by us in practice.

Electrical and Photometric Characteristics

A striking feature of electroluminescent panels is the rapid variation of brightness with operating voltage as already mentioned. For practical purposes the relationship may be expressed as a power law of the type:—

$$B = kV^n$$

where B and V are the brightness and applied voltage respectively and k and n are constants depending mainly on the nature of the phosphor and dielectric medium. The exponent "n" usually takes a value between 3.0 and 4.0. It will be noted that this value approximates to that for a filament lamp. That is to say, the light output of an electroluminescent panel and filament lamp connected to a common supply will maintain approximately the same ratio when the voltage is varied.

This marked dependence of brightness on voltage has an important bearing on the performance and reliability of an electroluminescent device. This light source is essentially a capacitor and for reliable operation requires an adequate margin between its operating and breakdown voltages. The rapid increase of brightness with voltage makes it tempting to push up the operating voltage nearer to the breakdown point in order to reach the highest possible brightness. This can only result in a sacrifice of reliability by increasing the risk of early failure. Should the use of electroluminescent devices become widespread, it would seem desirable to have an accepted basis on which to quote performance in terms of operating and test voltages. Apart from the question of performance, an adequate safety margin in voltage overload is also required to deal with line surges, switching transients and other voltage variations in the supply mains. Experience has indicated that panels with thin dielectric layers for operation in the range 100-150 volts should be tested at about twice the running voltage, which is in general agreement with test procedure for conventional capacitors. Thicker layers intended for running voltages of 240 or higher permit the use of a somewhat narrower margin between test and operating voltage. The necessary safety margin will depend on a number of factors of which the nature of the dielectric material and phosphor, and method of manufacture are the most important.

It is instructive to examine further the effect of the thickness of the dielectric layer on design and performance. The curve of Fig. 7 shows the relationship between brightness and dielectric thickness for a fixed applied field (as given by a constant ratio of applied voltage to dielectric thickness).

It will be seen that, for thin dielectric layers the brightness falls off due to the small amount of phosphor present. For thicker layers, the brightness increases less rapidly and tends to approach a steady value, since light generated deep in the layer is lost by absorption before it can escape through the front surface of the device. Thus there is little to be gained by increasing the thickness and operating voltage indefinitely with existing materials. The greater safety margin necessary for panels of low design voltage, i.e., with thin dielectric layers, further reduces the useful brightness at this end of the thickness range.

Table 1 shows the brightness values for a series of experimental green panels designed for operation from specific supply voltages, with adequate safety margin. It

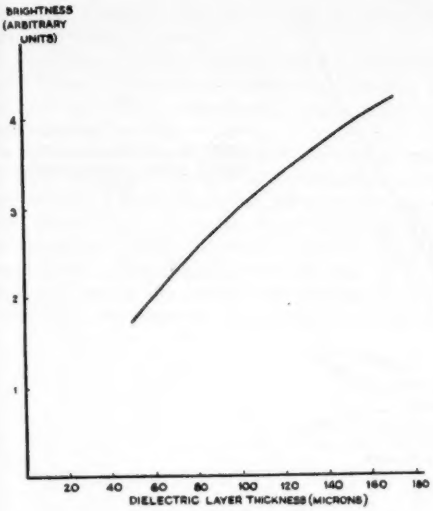

Fig. 7 (left). Relationship between thickness of dielectric layer and brightness for a constant applied field.

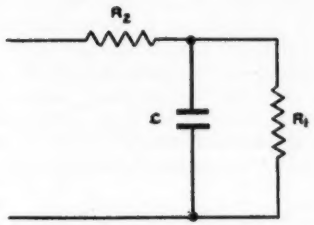

Fig. 8. Simple equivalent circuit for an electroluminescent panel.

Table 1

Brightness Data for Experimental Green Electroluminescent Panels designed for a Range of Supply Voltages, Frequency 50 c.p.s.

Operating Voltage	Brightness at Operating Voltage (Foot-lamberts)	Brightness near Breakdown Voltage (Foot-lamberts)
110	0.1	1.3
240	0.67	5.75
415	2.2	7.7

will be noted that the brightness increases markedly with design voltage and study of this factor indicates that the optimum operating voltage with existing materials is in the region 600 to 800. By operating in the region of the breakdown voltage greatly increased brightness values can be obtained, as shown in the third column of the table.

For the purpose of making electrical measurements, an electroluminescent panel may be assumed to possess the properties of a capacitor with high dielectric loss. The much simplified equivalent circuit shown in Fig. 8 may be taken as a capacitor C and resistance R_1 in shunt. The resistance of the transparent conducting layer R_2, which is effectively in series with the capacitor, may usually be neglected. The wattage input to the panel may be considered as dissipated in R_1. By far the larger proportion is heat loss in the dielectric layer, only a very small amount being emitted as light. The value of the capacitor and shunt resistance are both voltage and frequency dependent[24, 30].

Fig. 9 shows the percentage variation with applied voltage of a number of electrical and optical characteristics of a typical green electroluminescent panel. The values of these characteristics at the operating voltage are given in Table 2.

It will be seen that the maximum efficiency of about 3.5 lm/w occurs at a voltage about 30 per cent. above the nominal value and thereafter decreases. It is clear that a much better all round performance would be obtained by operating at the maximum

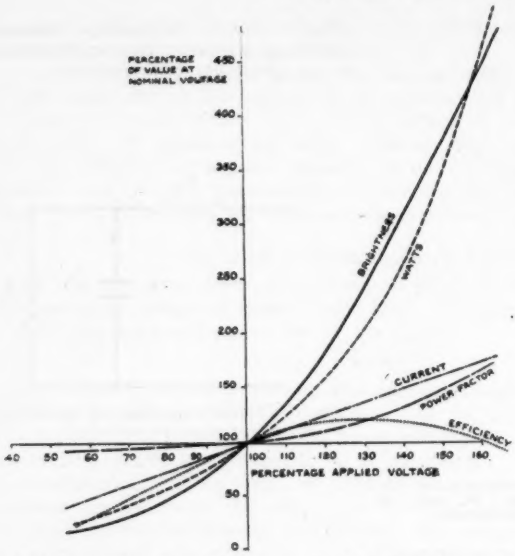

Fig. 9. Effect of applied voltage variation on characteristics of a typical green electroluminescent panel.

efficiency point, but this is not possible at present, since the running voltage would be brought too near to breakdown for reliable operation.

In common with all electric light sources, the light output of an electroluminescent lamp depreciates during life. In early experimental panels the deterioration was rapid, but with intensive study the lumen maintenance has now been brought up to an acceptable level. Further improvements will, however, be needed to bring it to the standard achieved by conventional sources. One of the main causes of depreciation is the ingress of moisture and other contaminants to the dielectric from the atmosphere. This can be largely prevented by covering the back of the panel with a layer of glass sealed with paraffin wax or by the use of a thick layer of resinous or plastic material impervious to moisture. Fig. 10 shows a typical lumen maintenance curve for a green panel. The steep rise to about 125 per cent. of the initial brightness in the first 100-200 hours is an unusual feature which so far has not been fully explained. It may be due to the shrinkage of the dielectric layer during the early stages of life or possibly to movement of the phosphor particles in the dielectric to a more favourable orientation. This initial rise is followed by a fall in brightness to about 75 per cent. of the initial value at 3,000 hours, after which the output remains substantially constant. Deterioration in light output may also be due to interaction of the phosphor and

Table 2

Performance Data for a Typical Low Voltage Green Electroluminescent Panel

Operating voltage	110
Frequency	50 c./s.
Current	0.55 mA.
Power factor	0.1
Consumption	0.006 watt
Light output	0.018 lumen
Efficiency	3 lm/w
Effective panel area	25 sq. in.
Brightness	0.1 ft.-lambert

dielectric medium. Photo-blackening of the phosphor subjected to an electric field has also been observed.

Excellent lumen maintenance performance has been obtained with the electroluminescent bulb already mentioned. In this construction the bulb is filled with dry nitrogen or other neutral gas which fully protects the dielectric layer from contamination.

Failure of electroluminescent devices is usually due to breakdown of the dielectric in much the same manner as a capacitor failure. The puncturing of the dielectric is followed by a small discharge between the two plates which may cause cracking of the glass sheet. In some cases the original breakdown is self-extinguishing and the panel continues to function normally with the exception of a small black spot at the breakdown point. The life of a panel is also affected by the ingress of moisture, which can seriously reduce the breakdown voltage of the dielectric layer. It can, however, be stated that the potential life of electroluminescent devices is many thousands of hours

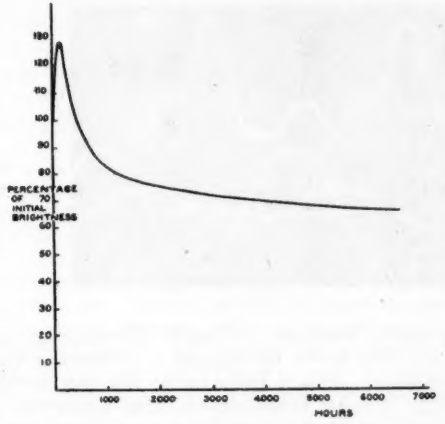

Fig. 10. Brightness maintenance curve for green electroluminescent panel operating at 240 v. 50 c.p.s.

provided they are soundly constructed and operated with an adequate margin between operating and breakdown voltages.

Much useful fundamental information has been obtained by the study of light output waveforms of electroluminescent panels, powder cells and single crystals, but only a brief account of this aspect of electroluminescence is possible here[23, 24, 31]. Fig. 11 (a) shows the light output waveform for a typical panel operating from an AC supply with corresponding waveforms of the applied voltage and current. A pulse of light is emitted each half cycle in phase with the power input to the panel, the peak occurring slightly in advance of the voltage peak. One or more subsidiary pulses lagging behind the voltage can usually be detected.

Examination of the light emission from single phosphor crystals or from very thin layers of crystals excited in an alternating field shows that in general a higher proportion emerges in the direction of the negative electrode. That is to say light is emitted in approximately equal pulses in alternate directions from the crystal layer each half cycle. In a normal panel with a back electrode of high reflectivity, light emitted towards this electrode is reflected forwards and the light waveform, as seen from the front of the panel, is a succession of nearly equal peaks, one for each half cycle. Slight differences in the height of successive peaks can just be seen in Fig. 11(a) probably due to loss on reflection at the rear electrode and by absorption in the dielectric. As might be expected, a non-reflecting layer for the back electrode, such as

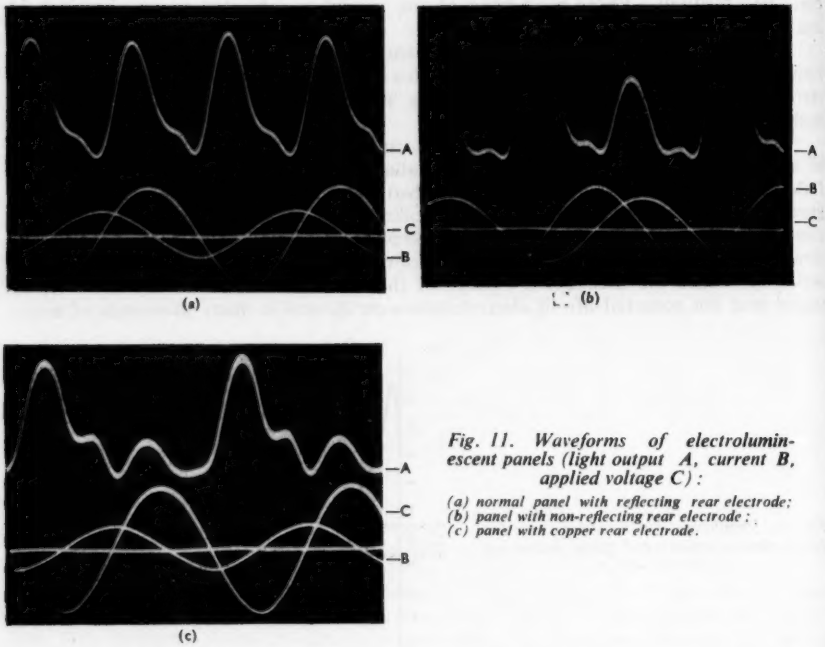

Fig. 11. Waveforms of electroluminescent panels (light output A, current B, applied voltage C):

(a) normal panel with reflecting rear electrode;
(b) panel with non-reflecting rear electrode;
(c) panel with copper rear electrode.

graphite, enhances the height difference in successive peaks as seen in Fig. 11(b). Fig. 11(c) shows the marked asymmetry in light waveform obtained with a copper electrode. This is found to be due, not to absorption and reflection effects, but to large intrinsic differences in light output on positive and negative half cycles, the larger output occurring when the copper layer is negative. Contrary to what might be expected, no current rectification is found.

The effect of increasing the frequency of the supply is to increase the number of pulses of light emitted per second without substantially reducing the pulse height. The light output therefore increases linearly with frequency to about 1,000 c.p.s. when a saturation effect begins to intervene, as shown in Fig. 12. Brightness values in excess of 50 ft.-lamberts are possible by operating panels under limiting conditions of voltage and frequency, but with marked impairment of life and maintenance.

Increasing frequency also produces a colour change towards shorter wave-lengths in certain green phosphors exhibiting a blue emission band in addition to the green. This is due to the partial suppression of the green band at higher frequencies[32].

An interesting effect found by the authors[33] concerns the light emission properties of an experimental cell in which the dielectric consists of a relatively thick compacted layer of electroluminescent phosphor crystals between two transparent conducting glass sheets, no dielectric bonding medium being used. Values of light output are comparable with normal panels, and the emission is similarly directed towards the negative electrode each half cycle.

Passage of direct current through the cell for a few minutes induces a polarisation effect with marked increase in impedance, and a weak emission of light towards the anode. On applying an alternating voltage it is found that light is emitted only towards the electrode which served as anode during the DC conditioning. Light

emission towards the original negative electrode is completely suppressed. The cell slowly reverts to symmetrical light output by continued operation on AC.

Careful drying of the phosphor suppresses completely the light emission of the cell, but this is restored on exposure to moist air. This suggests that the surface conductivity of the phosphor crystals is an important factor in this phenomenon.

Applications

It is perhaps a mistake to consider electroluminescent devices as comparable in any way with conventional light sources. When lamp research laboratories began, a few years ago, to take an interest in electroluminescence there was a tendency to think that this new method of producing light might become a worthy successor to fluorescent and filament lamps for general lighting purposes. After several years of research effort, however, the light output, loading and efficiency of the new source remain disappointingly low, and general purpose lighting by electroluminescence seems unlikely in the immediate future.

Electroluminescence nevertheless provides a large area, low brightness source of unique thinness in white and a range of colours. In panel form the thickness may be as little as $\frac{1}{8}$ in. and satisfactory fittings may be designed which are less than 1 in. in depth. These characteristics render electroluminescent panels well suited for low level lighting where space is restricted, for lighting in silhouette, and for luminous signs and indicators.

Electroluminescent bulbs may be used in any normal BC holder connected to an appropriate AC supply where a lower power source such as a night light or indicator lamp is required. Employing the conventional 100-watt filament lamp bulb, these lamps consume about $\frac{1}{4}$ watt at 240 volts and give an output of about $\frac{1}{2}$ lumen for the green colour.

A specialised and important application of electroluminescence is the lighting of processing rooms in the photographic industry. In the handling of photographic film, only the illumination of vital equipment by sources "safe" to the emulsion in question can be permitted. This lighting is at present provided by the conventional safe-light consisting of one or more vacuum filament lamps inside a metal or plastic housing behind a gelatine filter of suitable transmission characteristics. The cooling

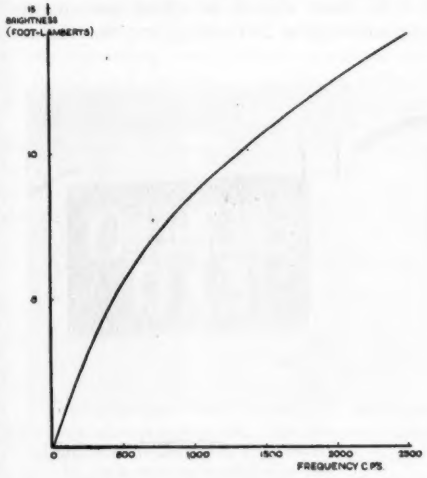

Fig. 12. Effect of frequency on light output of a green electroluminescent panel.

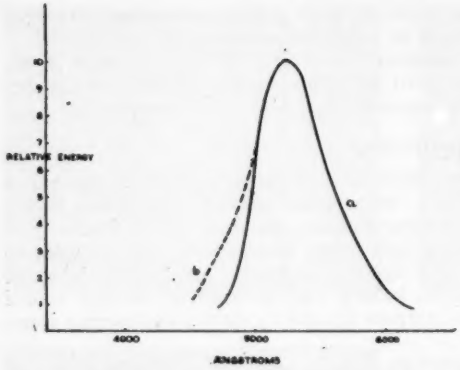

Fig. 13. Spectral energy distribution of a green electroluminescent phosphor: (a) green phosphor for darkroom safe-lights; (b) phosphor showing blue band extending emission into the actinic region.

of the housing necessary to prevent rapid deterioration of the filter presents a difficult problem since the provision of adequate ventilation is incompatible with prevention of leakage of white light from the box.

The brightness level of, for example, a green panchromatic safe-light is in the range 0.01 to 0.1 ft.-lambert. Green electroluminescent panels of this brightness can readily be constructed with suitable spectral emission characteristics and adequate life and maintenance. To enable the panel to be used without a filter, care must be taken in the preparation of the phosphor to ensure the almost complete elimination of the highly actinic blue emission band which can arise in copper activated zinc sulphide (see Fig. 13). Fogging tests on panchromatic film have shown that the electroluminescent safe-light has a performance in this respect comparable to that of the conventional article. A comparison of the luminous efficiencies of the two types of source is striking. The electroluminescent safe-light proves to be over 50 times more efficient.

An electroluminescent dark-room light using two panels each 7½ in. square is illustrated in Fig. 14. This is in the form of a shallow plastic box with removable acrylic plastic front cover. It is about 1 in. deep overall or about one quarter the depth of a conventional housing. The consumption at 240 volts is less than 1 watt.

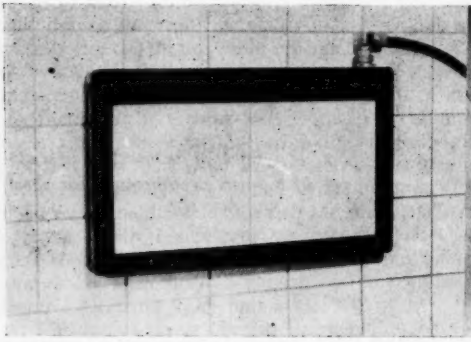

Fig. 14. Large panchromatic safe-light using two 7½ in. square panels.

Fig. 15. Electroluminescent direction sign for darkrooms using the safe-light shown in Fig. 14.

A small-scale commercial production of green electroluminescent panels and fittings for photographic dark-room use has been in progress for about 18 months in this country.

The availability of yellow and red panels and bulbs in addition to green would of course greatly extend the scope of this particular application of electroluminescence. Yellow and red safe-lights are generally used at much higher brightness levels than green. As already mentioned, no satisfactory red electroluminescent phosphors have yet been developed. Yellow electroluminescent phosphors are, inherently, only about one-half as efficient as green, and the brightness of yellow panels or bulbs will need to be considerably increased to achieve a satisfactory level for dark-room purposes. Increased brightness can be obtained by designing panels for higher operating voltages, but the need for a step-up transformer with associated problems of safety makes the idea less attractive for dark-room applications.

Photographic processing establishments employ a variety of exit and other direction signs, all of which must be safe to the particular emulsion in use. The safe-lights already mentioned may be readily adapted for this purpose by inserting in front of the panel the required legend cut in silhouette as shown in Fig. 15.

There are many other possible applications of electroluminescent panels as low-level illuminants where space is restricted, such as the lighting of theatre and cinema gangways, the marking of obstructions, or the insertion of panels in the "risers" of isolated steps. Uses of this type are at the moment restricted to relatively dark locations where space is limited. More widespread application will follow as brightness improves with further development.

The application of electroluminescence to instrument dial lighting[34] is an attractive possibility especially where high-frequency supplies are available, such as in aircraft. Many of the difficulties of stray light, uneven illumination and spurious reflections associated with the existing systems are avoided. The illumination of electric clocks, particularly for domestic use, is a somewhat special case of this application in that the electroluminescent dial would be expected to last the life of the clock, at least 50,000 hours. In alarm clocks the required life would be greatly reduced by providing a press button for energising the dial by hand, or a contact operated by the clock mechanism, which switched on the dial for a set period when the alarm sounded.

The development of a white electroluminescent phosphor mixture with good colour rendering would lead to a simple unit for the display of colour transparencies in foyers and the like. To obtain sufficient brightness a separate audio-frequency generator could be used to supply a group of display units.

Another significant application of electroluminescence is for image intensifiers for television. One or two articles and patents have already appeared on this subject in the United States and elsewhere[35, 36]. It is envisaged that future television receivers may well consist of a screen, about the thickness of a picture frame, which can be fixed to the wall and supplied by a cable from a conveniently hidden set.

Conclusion

An attempt has been made in this paper broadly to present the more important features of electroluminescence and to indicate its present and future possibilities. For those who wish to go more deeply into the subject, an additional list of references is included, which, together with the published work mentioned in the text, makes a fairly comprehensive bibliography.

This growing, and sometimes conflicting, technical literature itself reflects the activity and interest of research organisations in this new field. Nevertheless, current development work on electroluminescence has not yet led to anything other than rather special applications, and many uses for which electroluminescence appears

well suited must await considerable improvements in brightness, colour and manufacturing techniques.

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Discussion

DR. S. T. HENDERSON: The authors are to be congratulated on a stimulating paper and their excellent demonstrations. This Society is, of course, interested in any new light sources, and here is one with possibilities, which after its somewhat slow start may develop into something big. I agree that applications of it should be only in cases where its peculiar features are exploited, namely large area, uniformity, thin construction and, at present (unfortunately), low brightness. The photographic applications are evidently best at the moment. Our work also concurs with the efficiency figure

of 3-4 lm/w, and it will be of interest to see the plates of 10 lm/w promised for the forthcoming Physical Society exhibition.

This paper is, of course, largely concerned with the authors' own work, with due honour paid to Destriau. I remember the polite scepticism which greeted Destriau's account of his work, given at Oxford in 1938 soon after the discovery of the effect. To put the subject in perspective it should be recorded that, though Destriau continued his work, the next major advance was in 1949, when an American company produced a commercial lamp. I think it fair to say that all subsequent work, here and in U.S.A., was inspired by this achievement.

The constructional details given by the authors are important, and advances in efficiency may well depend on such details. Probably the phosphor offers the greatest possibilities of improvement, while improved dielectrics are also worth serious study.

Electroluminescence is rather unfortunate in the power supplies readily accessible. It could in its present state use higher voltage or frequency with advantage. As an example of what can be done in another direction, two of my colleagues, Mr. F. Oakes and Mr. D. H. Mash, have shown that a transistor circuit using a 9-volt dry battery can provide sufficient power (about 200 v.a.c. and 200 c/s) to run a small electroluminescent plate, which will be demonstrated later in this discussion.

As regards theory, the authors have wisely not attempted to go too deeply into this confused and difficult subject. No doubt when the theory of electroluminescence has been made more precise it will have a valuable bearing on luminescence theory, as well as help in predicting improved methods for using electroluminescence. These more rarefied discussions must not be ignored, but so far the experimental approach has produced the most striking results. In conclusion, electroluminescence has many aspects and should interest members of varied outlook.

DR. G. F. J. GARLICK : With respect to the fundamental mechanism of electroluminescence it is very difficult to draw any conclusions from studies of microcrystalline powder layers and the most consistent theory has been established for single crystals of zinc sulphide, notably by Piper and Williams(1) and by Alfrey and Taylor(2). There seems little doubt that a Schottky exhaustion barrier at the crystal surface (−ve side) provides the large fields (10^7V/cm) necessary to produce the collisional excitation of luminescence centres while the narrowness of the barrier inhibits dielectric breakdown. It is interesting to note that green-emitting single crystals of zinc sulphide made by D. R. Hamilton of my laboratory show feeble electroluminescence but this is much enhanced by subsequently diffusing copper into these crystals, a fact in agreement with results for powders but a technique allowing a more powerful approach to the fundamentals of electroluminescence.

MR. D. H. MASH : The reference in this paper to the relationship between brightness and voltage as a power law is interesting in view of the many functions that have been proposed for this. My own experience is that with blue and green-emitting phosphors the brightness increases linearly with the applied voltage beyond a certain field until breakdown occurs, but it is hard to decide whether this difference between my own experience and the authors' lies in the phosphors or in the construction of the panel. In the case of the yellow phosphor we are agreed that the rate of rise is superlinear. I believe this to mean that a straight-line portion of the curve will be reached when large enough fields can be applied without causing breakdown. (Brightness-voltage curves for typical yellow and green phosphors were shown.)

A second point of interest is in the limited application of electroluminescence owing to its requirement of an alternating voltage supply. To overcome this difficulty and to extend the applications to such cases as cars where A.C. is not available, my colleague

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Mr. Oakes has developed a compact transistor circuit, small enough to go in the pocket and giving an output of 200 v. at 200 cycles from a 9-volt battery source. (Demonstrated.)

DR. P. W. RANBY: In the literature we find references to carborundum, willemite, cadmium sulphide and selenide, and even organic materials, as electroluminescent materials, but demonstrations of the phenomenon always seem to use zinc sulphide phosphors. Have the authors any information on the electroluminescent brightness obtained from, say, carborundum and willemite relative to zinc sulphide, so that the magnitude of the effect from these other materials may be assessed?

MR. H. R. RUFF: Do not the authors consider that the very considerable research studies on electroluminescent phosphors have helped very considerably our understanding of phosphor behaviour and have in particular linked phosphors definitely with more conventional semi-conductors?

In their paper and demonstrations the authors have rightly stressed the necessity for allowing an adequate factor of safety between the working voltage of an electroluminescent panel and the voltage that would cause breakdown. In our work at Rugby we have found it helpful to consider the provision of maximum potential stress on the phosphor apart from its breakdown problem by providing a suitable additional dielectric layer. By improving the overall power factor the losses have been reduced and efficiencies approaching 10 lm/w of green light obtained. I would like to congratulate the authors on including a figure for approximate optimum efficiency 12 lm/w and it is interesting to realise that this figure is being approached.

There are a number of interesting auxiliary characteristics of electroluminescence. We made an amusing frequency meter for Mr. Davies' lecture here in 1953 using the phosphor whose colour changes with frequency from green to deep blue. The polarisation of the powder cell described and demonstrated is interesting; this phenomenon seems to be dependent upon moisture, so might provide a humidity detector.

The authors describe the type of application for which electroluminescence is suitable. Much work has gone into the improvement of the phosphors and the mechanical electrical and chemical stability of electroluminescent panels so that it would seem to us that while their brightness and efficiency renders unattractive their use as general lighting sources they are already able to perform a useful lighting service in the field of low brightness indicators.

DR. J. W. STRANGE: What intrigues me about this development is the way a very insignificant phenomenon was largely neglected for ten years and then suddenly received widespread attention and made quite considerable advances. The table of references and the introduction given by the authors tends to obscure the course of development. The first five references are to phenomena which are quite different from the one we are concerned with, which is the continuous production of light by a phosphor in an alternating field. The early references were to related but quite distinct phenomena.

I think there is little doubt that we owe to Destriau the first discovery of the effect and his first publication was in 1936. Like Dr. Henderson I was present at the Oxford Conference in 1938 and remember him presenting his paper and the polite disbelief with which we heard of luminescence being excited under those conditions by voltages as low as 60 volts. The authors in their paper stress the point, quite rightly, that such fields if uniform seem unlikely to produce any effect. This lukewarm reception, coupled with the war, undoubtedly accounted in part for the long delay until 1949. The group of American engineers listed in references (9), (15), (20) then got hot on the trail and rapidly brought it from being a mere curiosity to something that had commercial application.

Two techniques undoubtedly helped, one was the development of the hard dielectric

replacing the oil of Destriau, and the second was, of course, the production of conducting but still transparent glass. The other main feature was the purely empirical development of new phosphors including the important discovery of the value of lead as an addition during the activation process. The authors dealt rather summarily with the phosphors which were undoubtedly a vital factor in the development.

In conclusion I was very interested in Dr. Garlick's remarks. It seems, for once, that our theoreticians, aided by very able experimental work, will not only explain our empirical advances but will also show us the way to much greater advances in the future.

MR. A. H. MCKEAG : Reference has been made in the course of the paper and during the subsequent discussion to the fundamental work of Destriau on electroluminescence. The value of his results on the electroluminescent phosphors themselves has perhaps not been sufficiently stressed. Although, as a result of later work, the brightness of these materials has been increased many times, the early results of Destriau have been well substantiated.

It is perhaps remarkable that despite the intensive search for phosphors responsive to this form of excitation, the useful phosphors are, at present, restricted to zinc sulphides containing a relatively high copper content. From the theoretical aspect, it would be interesting to understand why the effect appears to be restricted to such a narrow range of materials.

MR. K. SCOTT : The authors have drawn attention to the importance of the type of phosphor necessary to produce the phenomena of electroluminescence, but little mention has been made of the physical aspects of the powder layer. In earlier work in this field, in our own laboratories and we believe elsewhere, difficulties were experienced due to discharges occurring between the plates, through air gaps and over crystal surfaces. These discharges, of course, produce visible and ultra violet radiation and thereby excite the phosphor by absorption of the ultra violet, as well as by direct ion bombardment. In the early days, in all attempts to transform the interesting electroluminescent phenomena into practical light sources, it was necessary to distinguish between the effect of these discharge phenomena and the true field effect.

Perhaps the most important aspect of these developments, however, from the point of view of the Illuminating Engineering Society is that which concerns the practicability of electroluminescent panels as competitive light sources. As an example, a 6-watt 9-in. fluorescent lamp operates at something more than 30 lm/w, whereas an electroluminescent panel gives 3 or 4 lm/w with a possible value in special cases, as given by Dr. Henderson, of 10 lm/w. I would, however, like to draw the attention of the meeting to the wattage which can be dissipated by a given area of panel as this obviously determines in a more fundamental manner than the overall efficiency the total light output. In our experience a panel of 5 in. sq. uses less than one-hundredth of a watt. It would be interesting to compute on the basis of the efficiency figures given in the course of this meeting what area of panel would be required to produce an acceptable level of illumination for general purposes and the wattage which would be dissipated.

It seems clear that a luminescent panel as far as can be visualised at the moment is destined to be a special purpose device rather than a serious competitor with any existing light source.

MR. G. E. B. WHITE : Reference has been made in the paper and discussion to the metal rectifier which consists of a conductor and a semi-conductor with rectification occurring at the intimate junction between the two. The electroluminescent device by definition consists of two conductors between which are the phosphors dispersed in suitable insulating material acting as the dielectric. Under these conditions there

appears little ground for rectification between the two conductors as is confirmed by the results in the paper.

Mr. H. G. JENKINS: I am more than glad that in the paper and in the discussion full recognition has been given to the pioneering work of Destriau in this field. Whatever may transpire in the future, when medals are being presented for the discovery of electroluminescence, this Society may claim to have given credit where it was due

There are two points I would like to make. Firstly, I think the significance of the luminous efficiency of these devices may be overstressed. Even if the present achieved efficiency is doubled the light output is still too low to be of much practical use and this situation will continue unless, in addition, the wattage dissipation in the lamps can be materially increased. My second point refers to the possibilities of utilising the phenomenon in the field of television and it might be of general interest if the authors would enlarge on the possibilities here.

Mr. C. H. WALKER: I would like to ask if the authors support my contention that the work carried out on electroluminescence with a view to securing the maximum efficiency of light production for a given power input is of definite value in order to support the various theories which have been put forward. Mr. Ruff has pointed out that by attention to phosphor and general design of the panel we have now approached the maximum efficiency proposed on the basis of present theories. Whilst I would agree with Mr. Jenkins that the important practical application features at present are maximum brightness irrespective of efficiency surely on a long-term basis efficiency is very important. I was interested in Dr. Garlick's mention of higher efficiencies obtained on single crystals of zinc sulphide by attention to activation and would like to know how much greater efficiencies than 4 lm/w have been attained.

The references to suggestions put forward in the United States with regard to the application of electroluminescence to television are interesting. Clearly any system which depends on the scanning of a large number of cross-over conductors at right angles to each other similar to the interesting but simpler map plotter demonstrated by the authors, would be fraught with difficulties at the present stage of the art. A mechanical system would be very unlikely, and any electronic system, even with the advent of transistors, would seem some way off. The attainment of adequate contrast would also seem difficult in view of the map plotter demonstration, which gave considerable brightness at cross-over points adjacent to the one being excited. The most practical solution at present would seem to be on the basis of a light amplifier cell which has been demonstrated in the United States.

Here a photo conductive substance is superimposed on a layer of electroluminescent phosphor, the electrodes on each side of the phosphor and photo conductive substance being capable of transmitting light. Light rays from a low brightness source such as a small cathode ray tube are focused on to the photo conductive layer causing a proportional reduction in the resistivity of the photo conducting substance beneath them. This increases the field across the phosphor and either increases or reduces (as Dr. Garlick has suggested for superior contrast) the light emitted by the phosphor at these corresponding points.

Finally I should like to ask the authors if their experiments with a copper backing layer had produced any improvement in brightness and/or efficiency.

THE AUTHORS (in reply): We would like to thank those who have contributed to the discussion for their interesting and stimulating remarks.

In preparing this paper, we have tried to cover, in addition to our own contribution, the more practical aspects of the work in this field, which is now being carried on in a

number of industrial and university laboratories. As Dr. Henderson has rightly said, this work on both sides of the Atlantic owes its inspiration to the pioneer work of Destriau. It is also significant, as pointed out by Mr. McKeag, that no other electroluminescent phosphor giving a useful brightness has been found other than those which Destriau studied.

In reply to Dr. Strange, we would agree that the first five references are to related but somewhat different phenomena, but these were included for completness. Although the 1936 date for Destriau's original contribution is given in the written paper it is true that the appropriate reference was omitted. (This has now been included.) Destriau's important 1947 paper in the Philosophical Magazine, to which reference is made, covers fully all his earlier work on electroluminescence.

Dr. Garlick's reference to his work on single electroluminescent crystals was particularly interesting. It is perhaps mainly in the direction of fundamental studies of this nature that we must look for the next stage in the improvement of electroluminescent devices. Any hint would be welcome of the ultimate possibilities in brightness and efficiency which this work might yield.

In reply to Mr. Mash's remarks concerning an approximately linear relationship between brightness and applied voltage for certain green- and blue-emitting phosphors, we have found a tendency for the brightness-voltage relationship to move towards linearity in highly stressed green-emitting panels. The power law relationship connecting brightness and voltage is really only adequate over a limited voltage range, and certain more exact exponential functions have been proposed, which indicate a point of inflexion and ultimate saturation of brightness. It is, therefore, not unreasonable to expect some straightening of the characteristic of practical panels as the breakdown voltage is approached. The battery-operated electroluminescent sign, employing a transistor circuit, shown by Mr. Mash, is an interesting example of a combination of two branches of " Solid Physics."

Referring to Mr. Ranby's inquiry concerning the use of electroluminescent substances other than zinc sulphide, we have no quantitative data on the relative brightness of such materials. As already mentioned, it is surprising that the combined efforts of the workers on this subject have failed to discover an electroluminescent phosphor to approach in performance copper activated zinc sulphide.

Mr. Ruff rightly emphasises the need for increasing the electric stress on the phosphor in an electroluminescent panel whilst maintaining an adequate safety margin between operating and breakdown voltage, also for reducing internal losses and improving power factor as a means of increasing efficiency. But, as pointed out by Mr. Jenkins and Mr. Scott, the immediate need is to increase the wattage loading per unit area rather than the efficiency to enable electroluminescent devices to be more widely applied. On a long-term basis, efficiency must, of course, be improved, as Mr. Walker has mentioned, before electroluminescent lamps can be used for general lighting purposes.

Replying further to Mr. Scott, it is indeed true that the number of applications for which electroluminescence is ideally suited are still very limited, but we feel that this should not be allowed to detract from a study of this fundamentally new method of producing light.

Mr. Walker has kindly given us a brief description of the electroluminescent image intensifier for television of a type being studied in the U.S.A. and elsewhere, and to which we referred in the written paper. We did not perhaps make it sufficiently clear in our description of the map-plotting device that there was no intention of proposing this for television purposes. The circuit problem involved in energising a multiplicity of cross-over conductors in order to build up a picture would certainly be formidable.

In reply to Mr. Walker's and Mr. White's queries regarding the copper backed electroluminescent cell, we did not expect to find current rectification, but it appeared

to be a point well worth checking in view of the marked difference in light output on successive half cycles. As far as it was possible to judge from the relatively small number of cells of this type made, there was no marked improvement in their performance over conventional types.

Additions to the List of Members

The following applicants have been duly elected by the Council to membership in the Society and their names have been added to the list of members:—

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